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Modeling of Pro-supination for Forearm Skeleton Based on MRI ⋆

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Abstract: The continuous passive motion (CPM) device we developed for the elbow joint implements pro-supination of the forearm naturally accompanying flexion and extension of the elbow joint. As the method of making the curative effect due to accompanying pro-supination clear, the range of motion (ROM) of the forearm skeleton are estimated by using of the pro-supination model of the forearm skeleton. As the pro-supination model of the forearm skeleton, there are the models Fick and others and Kecskemethy and others proposed. But, hypothesis is set in regard to the link length of the model and the rotation axis of the forearm. So, in the case of pro-supination of the forearm, it is thought that mismatch happens between the forearm skeletal model and the forearm skeleton. In this paper, by analyzing magnetic resonance imaging (MRI) of the forearm, we proposed the newer forearm skeletal model based on the biomechanics.

1. INTRODUCTION

As the population ages and fewer babies are born, it is an emergent issue to develop the technology for supporting and assisting the life to enhance the human quality of life (QOL). Especially in medical field, not only the rationalization of work but also the medical treatment and the rehabilitation making active use of robot technology have been tried out. One of such examples is continuous passive motion (CPM) device. CPM, advocated by Salter (1960), is a medical treatment in orthopedic surgery that aids recovery by continuously and externally moving joints after trauma or operation. Compared to existing treatment of applying a cast, the medical treatment using CPM as a result of contracture is confirmed of much more effect of curing damaged joint tissue, accelerating tissue regeneration, and ensuring range of motion (ROM).

CPM devices have been mainly applied to patients with knee joint disorder and there are many reported clinical cases, Sakaki et al. (1999), Sakaki et al. (1997), Miyamura et al. (2003). Contrary to this, there are few clinical cases of CPM device with upper limb joint disorder due to complexity of skeletal mechanism. Especially, Many of the CPM devices for elbow joint, which are tried out in practical clinic, restrain pro-supination of forearm due to convenience at medical scene and operate at 1 degree of freedom (DOF) to flexion and extension of elbow joint, just as the CPM devices for knee joint, Kawaji et al. (2006). However, the skeletal mechanism of elbow joint is more complicated than that of lower limb and the movement of elbow joint is not simply corresponded to it of 1 DOF. Actually, it has been known that pro-supination of forearm is implemented at a time of flexion and extension of elbow joint due to the characteristics of forearm skeletal mechanism, Yamaki (1999). Contrary to this, by using CPM device with 2 DOF for flexion and extension of elbow joint and pro-supination of forearm, we tried to realize more effective CPM device with impedance control for pro-supination, Matsunaga et al. (2007).

Because the human forearm has complicated link mechanism composed of radius and ulna, simply using the CPM device with 2 DOF is not enough, Thompson et al. (2002). Therefore, just measuring the flexion and extension angle and the pro-supination angle of the CPM device does not clarify quantitative CPM indicator of how spontaneous ROM is extended, even though it enables to figure out the macro movement of forearm.

One of the methods to clarify the evaluation of treatment using CPM is considered to evaluate ROM of each joint composed of radius and ulna by using the skeletal model of forearm. Fick regarded forearm skeleton as closed link mechanism and proposed kinematics model, Fick (1904). However, natural pro-supination of forearm was not realized because the movement of ulna was fixed during pro-supination of forearm. Horiuchi et al. (1994) and Weinberg et al. (1997) proposed kinematics models of pro-supination that were closer to human motion, by analyzing the magnetic resonance imaging (MRI) scans. These models were just expressed the geometric relationship of forearm skele-

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ton by regarding the link mechanism of forearm skeleton as the rigid body, similarly to Fick (1904). On the other hand, Kecskemethy et al. (2005) considered the influence of elastic structure between each joint of forearm, such as ligaments, proposed kinematics model of pro-supination by homogeneous transform matrix and derived forward kinematics and statics. But, the hypotheses are set in regard to the link length of the model and the rotation axis of the forearm for the purpose of easy when applied in practical clinic. So, in the case of pro-supination of the forearm using the CPM device, it is thought that mismatch happens between the forearm skeletal model and the forearm skeleton.

The purpose of this paper is to propose the forearm skeletal model based on the biomechanics that is effective to clarify each joint movement of forearm in CPM, by analyzing MRI of the forearm. We describe the disorder that we intend in CPM for the upper limb, the features of CPM device (AH706), Kawaji et al. (2006) developed in our laboratory and the experiment result in case of using AH706. Secondly, we introduce about anatomical knowledge of the forearm skeleton provided in the previous studies and describe the characteristics of the forearm skeleton model proposed based on it and those problems. To propose the newer forearm skeletal model based on the biomechanics, we describe the MRI photography that we performed and the analysis results. In addition, the modeling of the forearm skeleton based on the analysis results are omitted because of the limitation of the extended abstract.

2. ACTUAL STATUS OF CPM FOR UPPER LIMB

CPM for upper limb is aimed to improve the limitation of ROM for the shoulder and elbow joints, after operations for arthritic disorders of the scapulohumeral joint and elbow joint, i.e. periarthritis humeroscapularis, contracture of the elbow joint and so on.

The contracture is the state that each joint causes the motion limitation for working on passively and automatically. The contracture is generally called a joint motion limitation to be generated by the articular capsule and the change of the soft tissue which is extracapsular formatio existing out of it. For the classification of the contracture, there are the classification about every each soft tissue that the lesion exists, the classification by congenital or acquired disorder and the classification by the cause, and so on. As the classification according to the joint formatio of the acquired contracture, there are 1) joint characteristics, 2) soft tissue characteristics, 3) muscular characteristics.

It is important for the prevention of the joint contracture that the promotion factors of the contracture are reduced as much as possible. There is the prevention of the edema for the one. The edema is the state that intercellular fluid in the articular capsule increase and pool. When CPM is applied for an elbow joint, the edema can be prevented by flexure and the extension of the elbow joint. But, it is unidentified how the joint should be moved for the contracture by the damage of a tendon and the ligament belonging to 2) same as the edema.

Fig.1 shows the CPM device (AH706) for upper limb developed in our laboratory, Kawaji et al. (2006). This device

Fig. 1. CPM device for upper limb (AH706), Kawaji et al. (2006)

is composed of control box, arm, ball-shaped gripper that enables pro-supination, supporting plate to decide the orientation of upper arm or upper body and remote operating switch. This device is the CPM device for elbow joint used at supine position, and it is composed of mechanism with 1 DOF that promotes flexion and extension of elbow joint without restricting pro-supination of forearm.

The rehabilitation with existing CPM devices is proceeded by complying with the joint angle and the arm's speed based on the diagnosis by medical professionals before rehabilitation. However, the CPM device cannot recognize the patients' pain during CPM and it is difficult to set the device optimally to the patients' conditions. Therefore, patients tend to feel pain around the terminal of ROM. We considered the patients as a part of feedback system of this device. That is, by using remote operating switch and repeated the joint movement in the range that they do not feel pain, ROM is gradually expanded and the contracture is improved by the method that patients update the movement range of device, Fukuda et al. (2005).

Also, the patients grip the handle to fixate their arm to the arm of the device in case with existing CPM devices, Fukuda et al. (2005). Therefore, complicated motion is not possible because the pro-supination of forearm is forcibly negated during flexion and extension of elbow joint. Contrary to this, in case of our device, the part where patients grip is made into ball-shaped gripper that freely spins, and the pro-supination of forearm is naturally promoted during flexion and extension of elbow joint.

In using the CPM device, it is necessary to analyze the effect of forearm motion during flexion and extension of elbow joint when the pro-supination of forearm is not restrained. For this analysis, we installed the encoder at the edge of arm of AH706 to measure extension angle of elbow joint θ_e[deg] and pronation angle of forearm θ_p[deg]. We performed the experiment that the arm movement of AH706 was set at 0.75[rpm] constant speed motion in the range of -60[deg]$\leq \theta_e \leq 90$[deg]. The subjects of the experiment was the healthy males. Fig.2 shows the relationship between θ_e and θ_p during the five-minutes CPM.

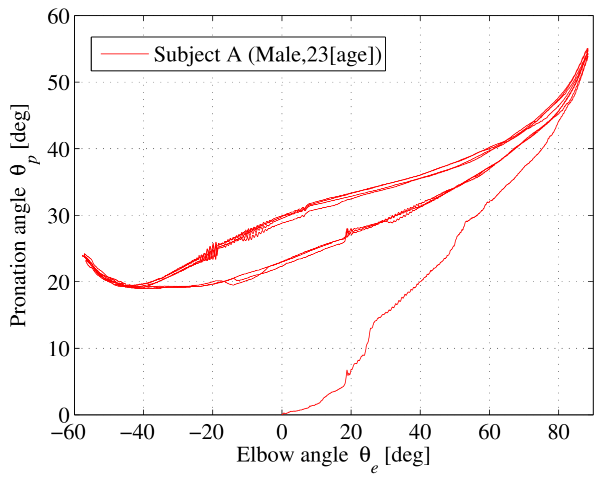

Fig. 2. Relationship between θ_e and θ_p in CPM without constraint

From Fig.2, pronation angle of forearm and extension angle of elbow joint represent almost constant trajectory when implementing CPM of elbow joint without restraining pro-supination. It is turned out that the forearm pronates with extension of elbow joint and supinates with flexion.

3. ANATOMY OF FOREARM SKELETON

The pro-supination of the forearm is the motion to occur between the radius and the ulna. Not only the radius, ulna, distal and proximal radioulnar joint, also the soft tissues, such as biceps brachii muscle, pronator teres, supinator and pronator quadratus, are implicated in pro-supination. Furthermore, as moving cooperatively with the radiocarpal joint and the elbow joint, the hand acquires a rotation angle for the humerus in a range of about 180[deg]. The rotation to say here points at motion for the axis.

In addition, when the convolution is rotation and the parallel displacement translation for 1 points of the universal space, convolution can express with combination of rotation and translation. Furthermore, the pro-supination is thought that relative motion between the radius and the ulna for proximal and distal radioulnar joints, that is the motion of the radius around the ulna.

This is called pro-supination in a narrow sense. The radius head is fixed to the ulna with annular ligament comparatively strongly in proximal radioulnar joint. In addition, both are connected with the triangular fibrocartilage complex and the articular capsule in distal radioulnar joint. On the other hand, the ulna and the humerus are connected with humeroulnar joint, and the radius and the hand are connected with the radius carpal joint. The convolution produces even distal than the radius carpal joint during pro-supination. It is said that there is movement to increase ROM of convolution in the humeroulnar joint. Hence, the pro-supination in regard to the appearance for upper arm of the volar aspect is larger than it of narrow sense. it is the comprehensive motion between two links which possess the ROM of about 80[deg] in pronationand 80-90[deg] in supination. This movement is called pro-supination of a wide sense.

4. PREVIOUS PROPOSED FOREARM SKELETAL MODEL

The pro-supination of forearm is shown by convolution movement of 1 DOF. Because the forearm composes of two bones, ulna and radius, more detailed models of pro-supination based on the forearm skeletal structure are required to analyze ROM in CPM. It is difficult to obtain a precise model due to the complexity of the bony form for forearm. Therefore, Fick et al. introduced the kinematics model under the thought that the skeleton of forearm is closed link structure, Fick (1904). The model can't reproduce the pro-supination as human beings because the movement of ulna during pro-supination is fixed. Contrary to this, by MRI scans, Horiuchi et al. (1994) has been verified that the ulna is not fixed with respect to the humerus, and the ulna sways laterally and slides along its axis during pro-supination. However, they are not considering the influence of joint motion by the elastic structure between joints, such as the ligament and the articular capsule, only by considering the geometric relation of the skeleton for forearm. For the kinematics of pro-supination, two kinds of displacements are relevant:

(1) the displacements between the two forearm bones and the humerus.
(2) the relative motion between the two forearm bones.

Kecskemethy et al. (2005) destructed the kinematics model considering the elastic structure between each joint of forearm. This is, in order to rotate the radius outwards, prismatic joint between A and B and rotational joint at C must be set as shown in Fig.3, Kecskemethy et al. (2005). In the figure, r_1 denotes the ulna, r_2 the wrist,

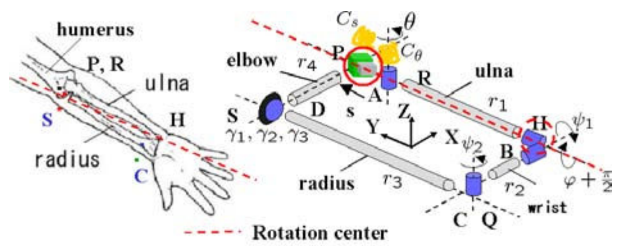

Fig. 3. The skeleton model for pro-supination, Kecskemethy et al. (2005)

r_3 the radius, and r_4 the elbow vectors. While P and R denote the axial displacement s and lateral swaying θ of the ulna with respect to the humerus, respectively. H is a Hooke's joint embodying the pro-supination angle ϕ and the torsional angle ψ_1 between radius and ulna, Q is the joint describing the aperture ψ_2 between ulna and radius, and S is the spherical joint represented by roll-pitch-yaw angles γ_1,γ_2,γ_3.

But, the hypotheses are set in regard to the link length of the model and the rotation axis of the forearm for the purpose of easy when applied in practical clinic. So, in the case of pro-supination of the forearm using the CPM device, it is thought that mismatch happens between the forearm skeletal model and the forearm skeleton.

5. MRI MEASUREMENT EXPERIMENT

In this paper, by using MRI, we photographed the forearm at pro-supination of the normal healthy adult and analyzed the image of the provided radius and ulna. MRI is diagnostic imaging to detect hydrogen atom density in vivo and is superior in the depiction of the soft tissue in vivo.

5.1 shooting procedure

The subject is an adult man of healthy 25 years old. We used the open-type MRI device (AIRIS-II; Hitachi Medico company), which has the magnetic field strength of 0.3T([tesla], 10000[gauss])(Fig. 4). As for the photography

Fig. 4. Sceen of MRI measurement

physique, in state face down, the elbow joint was extended about 80[deg], the subject grasped the grip part of hamper for forearm that we created by myself lightly, the pro-supination angles of forearm were set at -80, -50, -20, 20, 50, 80[deg]. 0[deg] for the forearm is assumeed rest position(Fig.5). We used the spin echo method for the

Fig. 5. Our original hamper for the forearm

pulse sequence.

To analyze skeletal movement of the forearm during pro-supination, we performed two experiments of photography of the normal pro-supination (Exp.1) and the photography of the ulna slide displacement(Exp.2). I show the photography condition of the each experiment 1,2 on the following table.

Shot condition of MRI scans			
	slice slice thickness[mm]	slice slice distance[mm]	field of view (FOV)
Exp.1	5.0	35.0	150
Exp.2	5.0	6.0	150
	repetition pulse (TR)[msec]	echo time (TE)[msec]	image matrix
Exp.1	500	25	256 × 256
Exp.2	450	25	256 × 256

The photography axle of experiment 1 is axial plane and it of experiment 2 axial and asagital planes. The photography time of experiment 1, 2 are 3[m]30[sec] and 4[m]30[sec], respectively.

5.2 MRI image analytical approach

Experiment 1 To analize the forearm skeleton motion during pro-supination, we mesured MRI scans in axial plane divided into 7 part from the elbow joint to the wrist joint, as shown in Fig.6.

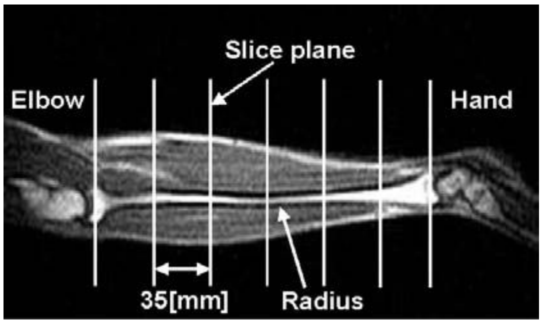

Fig. 6. MRI imaging for analizing the forearm during pro-supination

We extracted only the radius and the ulna which were the interest domain on a screen and calculated the center of gravity and the inertia main shaft from each image. To analyze relative motion of the radius and the ulna, We overlaped and translated the center of gravity of the ulna for each forearm angle. The rotation of the ulna does not changed, and the change of the main shaft expresses a spatial rotation of the ulna. Also, the change of the center of gravity of the radius expresses the convolution of the radius for the ulna and the displacement of the main shaft expresses "gap" of the radius. And We measured (1) the rotation center for the ulna of the radius during pro-supination, (2) the convolution angle of the radius center of gravity, (3) the change for pro-supination of the main shaft of the radioulna. In addition, the rotation center was required in the least-squares method. I performed the above-mentioned calculation with the program that I made in MATLAB.

Experiment 2 In fact, as has been verified by MRI measurements by Kapandji (1991), Horiuchi et al. (1994), and Weinberg et al. (1997), during pro-supination motion the ulna is not fixed with respect the humerus but performs a small swaying (lateral) motion as well as a small axial sliding along its axis with respect to the humerus bone. By this swaying and axial displacement motion, the tilting angle of the wrist can be reduced.

To mesure the sliding displacement of the ulna, We mesured around the elbow joint in axial and sagital plane(Fig.7). The measurement of the ulna slide displace-

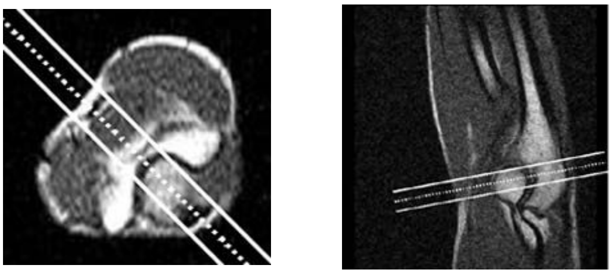

Fig. 7. MRI for the ulna sliding measurement

ment of Exp.2 used image analysis software, ImageJ.

6. ANALYSIS RESULT OF MRI

Fig.8,9 show original MRI scans we obtained and the images picked out forearm bone, radius and ulna.

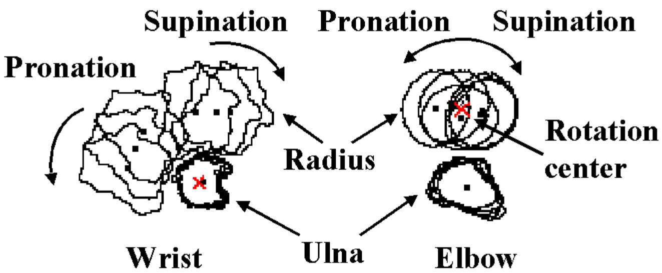

Fig. 9. Analysis result of pro-supination

The radius almost performs circular motion for the ulna. Each convolution center of proximal 2/7 part, the central part and distal 6/7 part were located on a straight line to be almost connecting the radial head and the ulnar head. However, the rotation center delicately varied with each forearm angle.

There was the change of the main shaft of the ulna during pro-supinaton within each 6[deg] in pronation and supination . The change of the main shaft occurred in the supination direction with pronated position and in the pronation direction with supinated position. On the other hand, the main shaft of the radius almost went to the rotation center during supi-pronation.

The pro-supination of the narrow sense is relative motion of a radius and the ulna. Each bone performs a rotation and a translation spatially. It is said that the convolution axis can be changed a position freely. In other words it is possible for the forearm to be circulated in an arbitrary axis such as the fifth finger, the first finger and the third finger. It is thought that both radius and ulna rotate with translation in the case of the motion around the third finger. On this account when analyzing pro-supination, it is difficult to decide an axis, and there are many reports regarding pro-supination as the motion around the ulna in convenience.

In this paper, for the motion around the third finger without moving a humerus as much as possible under a light grip, we overlaped the center of gravity of the ulna in circumstances of the calculation and the comparison and analyzed these. As a result, the change of the main shaft of the ulna, that is, the rotaion angle of the ulna were within each 6[deg] in pro-supination and these hardly rotated. In other words, in the case of the pro-supination of the middle finger circumference, the motion of the ulna mainly can be said to be the translation. The change of the main shaft, within 6[deg] of the ulna, produced in the pronation direction at supinated position in the supination direction at pronated position.

In case of only in a forearm, it is thought that The radius and the ulna were relatively rotated in the opposite direction in consequence of muscles. In addition, it is thought that it expresses a little rotation for the humerus of the ulna that the change of the main shaft of the ulna slightly occured, although it includes a measurement error. On the other hand, it is understood thet the motion of the radius mainly performs the motion of the rotation axis circumference for the ulna. It is said that the position of the rotaion center during pro-supination is located on the straight line that bound a radius head and an ulna head together. It almost agreed with this straight line on this analysis result. However, the rotation centers were slightly different with each limb position and these were not complete relative circular motion. In particular, in distal 2/7 part of the forearm The main shaft of the radius was slightly displaced to the palm side in maximam supinated position.

As for the rotation center delicately changing a position and the change of the radius main shaft large in the more distal position for the forearm, it is thought that "gap" produces so that the shapes of the radius and the ulna are different in the plane of distal radioulnar joint. In particular, in the maximam pronated position, the motion of radius is displaced from the circular motion around the ulna, to the palmar side. In the clinical case, it is said that the pro-supination of the forearm in the appearance is performed with plane passing through the volar aspect or the second and third metacarpal head with 90[deg] flexure position for the elbow joint. The position that plane passing through the volar aspect or the second and third metacarpal head becomes parallel to the humeralis major axis is regarded as the cadaveric position of pro-supination. However, there is uneasiness in plasticity of the decision of the cadaveric position so that the volar aspect not the uniform plane for the side arch which there is in the hand.

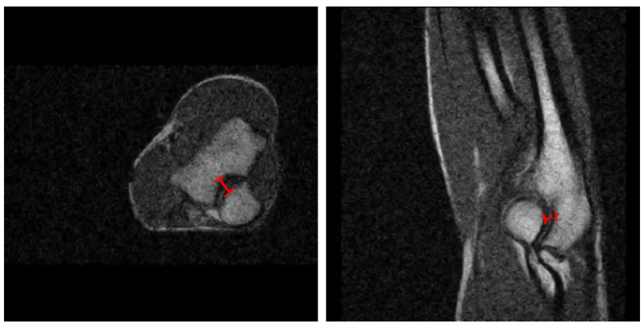

Fig. 10. MRI for the ulna sliding measurement

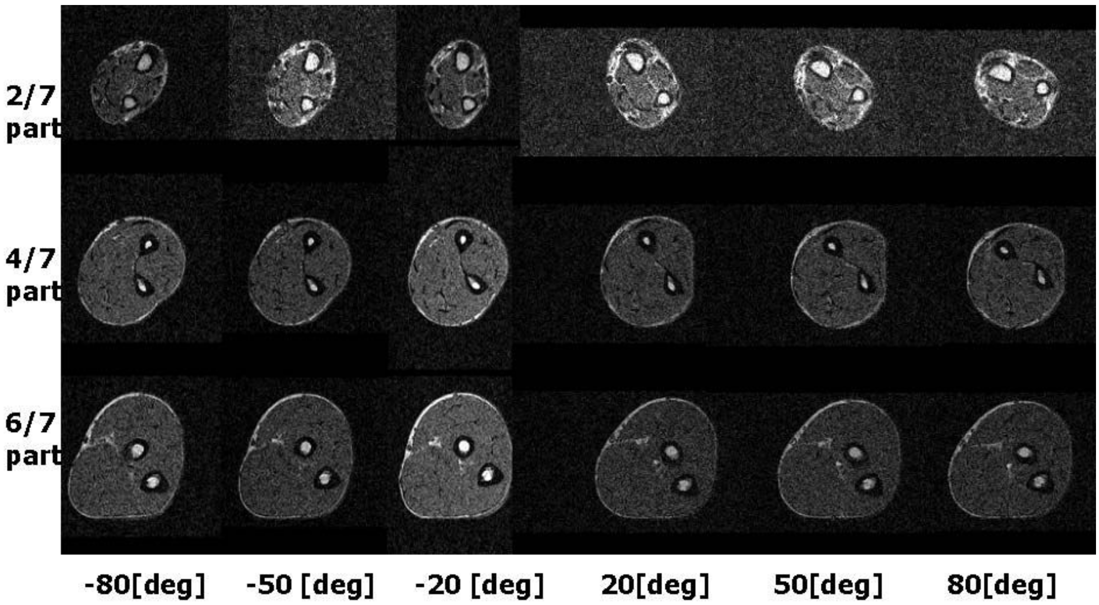

Fig. 8. MRI imaging of the forearm during pro-supination

Slide displacement of the ulna		
pro-supination angle[deg]	s [mm] in axital plane	s [mm] in sagital plane
-80	5.066	6.909
-50	6.247	6.397
-20	5.835	5.886
20	5.275	5.886
50	6.336	6.397
80	5.835	6.653

7. CONCLUSION

In the case of pro-supination of the forearm, for problem that mismatch happens between the previous proposed forearm skeletal model and the forearm skeleton, so that hypothesis is set in regard to the link length of the model and the rotation axis of the forearm. In this paper, we analyzed MRI image of the forearm. By the analysis results, we understood the sliding displacement of the ulna during pro-supination is symmetrically-displaced for rest position of the forearm, Unlike the previous study. Also, by analizing more detail relationships between the rotation center and link length of forearm bone, we are going to propose the newer model based on the biomechanics.

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